Status of Fragmentation Functions and Polarized Parton Densities

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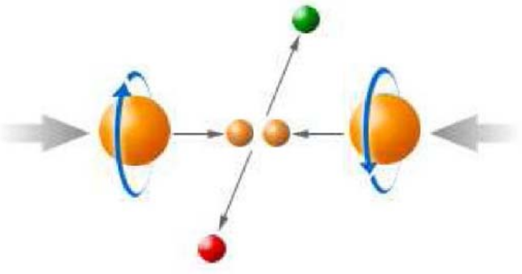
RIKEN

How can we use the successful framework of pQCD to further our understanding of nucleon structure and hadronization ??

determining spin-dependent parton densities from data



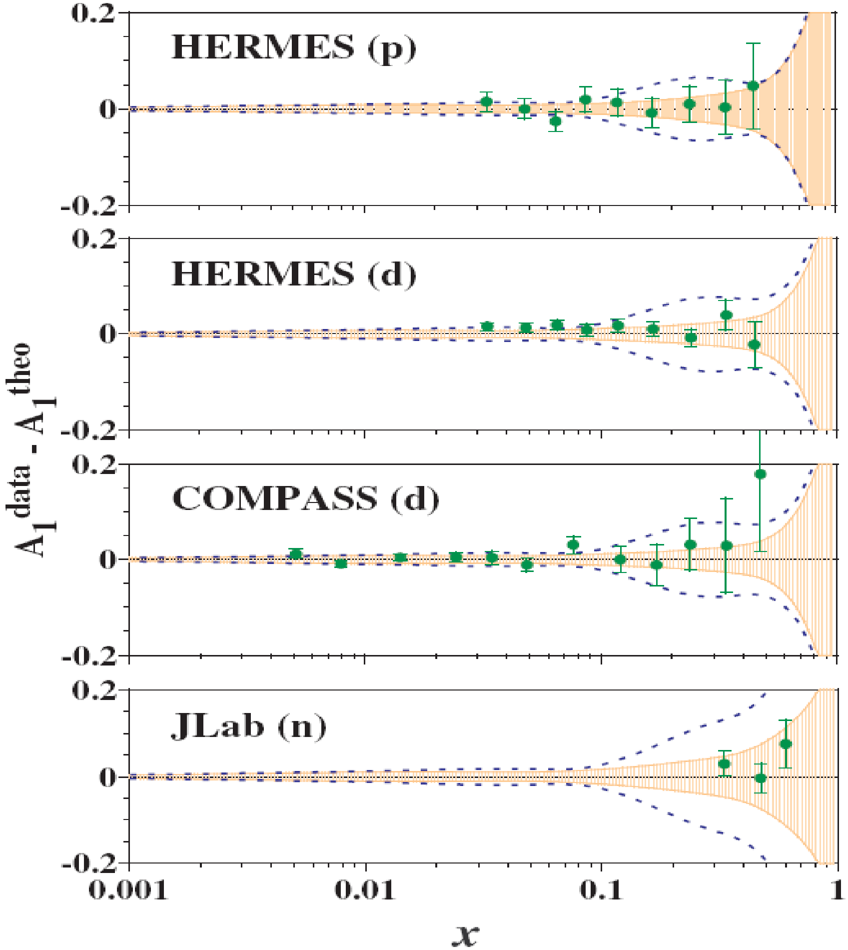
brief overview of the four most recent analyses

AAC PRD<u>74</u>(2006)014015; hep-ph/0612037	only DIS data, not fully up-to-date impact of PHENIX π^0 studied uncertainties (Hessian method)
Sassot et al. PRD<u>71</u>(2005)094018;<u>74</u>(2006)011502(R)	most comprehensive analysis so far DIS+SIDIS data impact of PHENIX π^0 studied uncertainties (Lagrange multiplier)
LSS PRD<u>73</u>(2006)034023;<u>75</u>(2007)074027	only DIS data but latest set uncertainties (Hessian?); HT fit uncertainties increase with time
COMPASS hep-ex/0609038;arXiv:0704.3600[hep-ex]	only DIS data but latest set 2 solutions for Δg with small errors

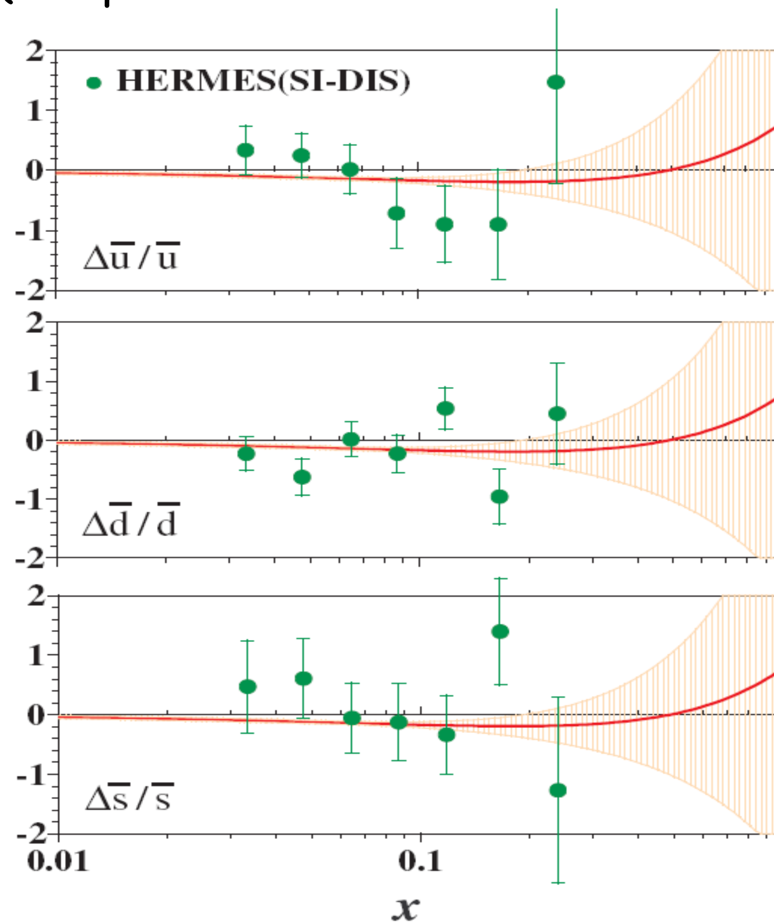
disclaimer: none of these four is a full global analysis

AAC analysis

Hirai, Kumano, Saito



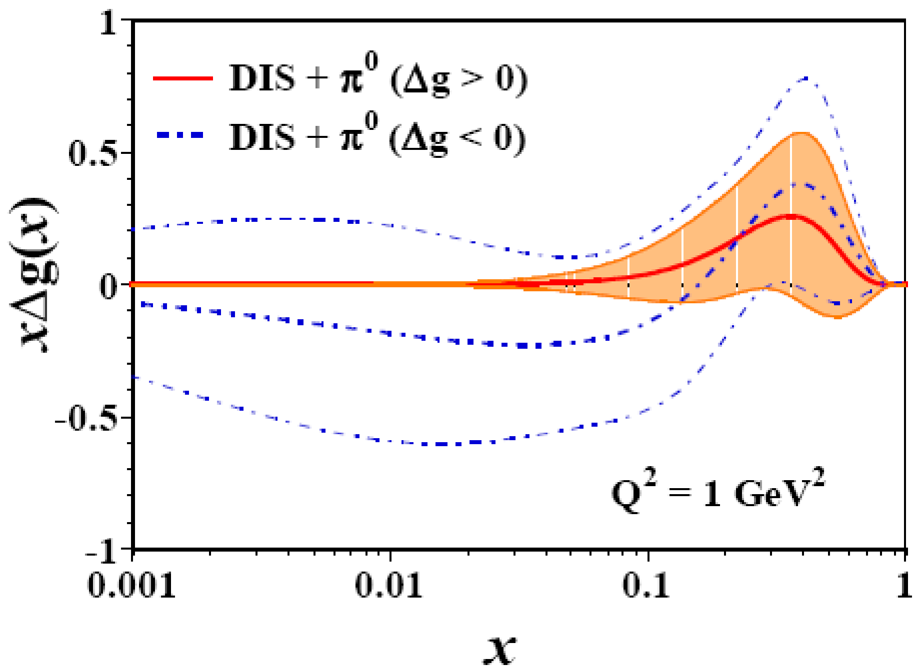
- only polarized DIS data fitted
- *assume* SU(3) symmetric sea
  (compatible with HERMES SIDIS data)



- pdf uncertainties: Hessian method

$$[\delta\Delta f]^2 = \Delta\chi^2 \sum_{ij} \frac{\partial \Delta f}{\partial a_i} H_{ij}^{-1} \frac{\partial \Delta f}{\partial a_j}$$

use $\Delta\chi^2 = 12.64$ for 1-σ errors



- **DIS only:** Δg unconstrained

[find $\int_0^1 \Delta g\,(x)\,dx = 0.47 \pm 1.08$]

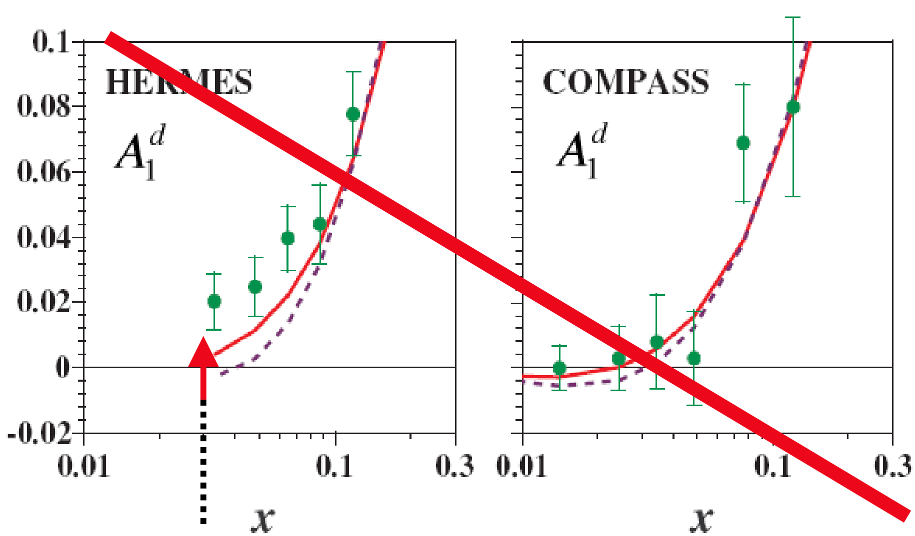
+pp data: large pos. Δg disfavored

[find $\int_0^1 \Delta g(x)\,dx = 0.31 \pm 0.32$]

but also $\Delta g < 0$ possible!

[find $\int_0^1 \Delta g(x)\,dx = -\,0.56 \pm 2.16$]

(similar to old GRSV analysis)



effect of positive Δg

additional new finding:

- "tension" in A_1 (deuteron) data

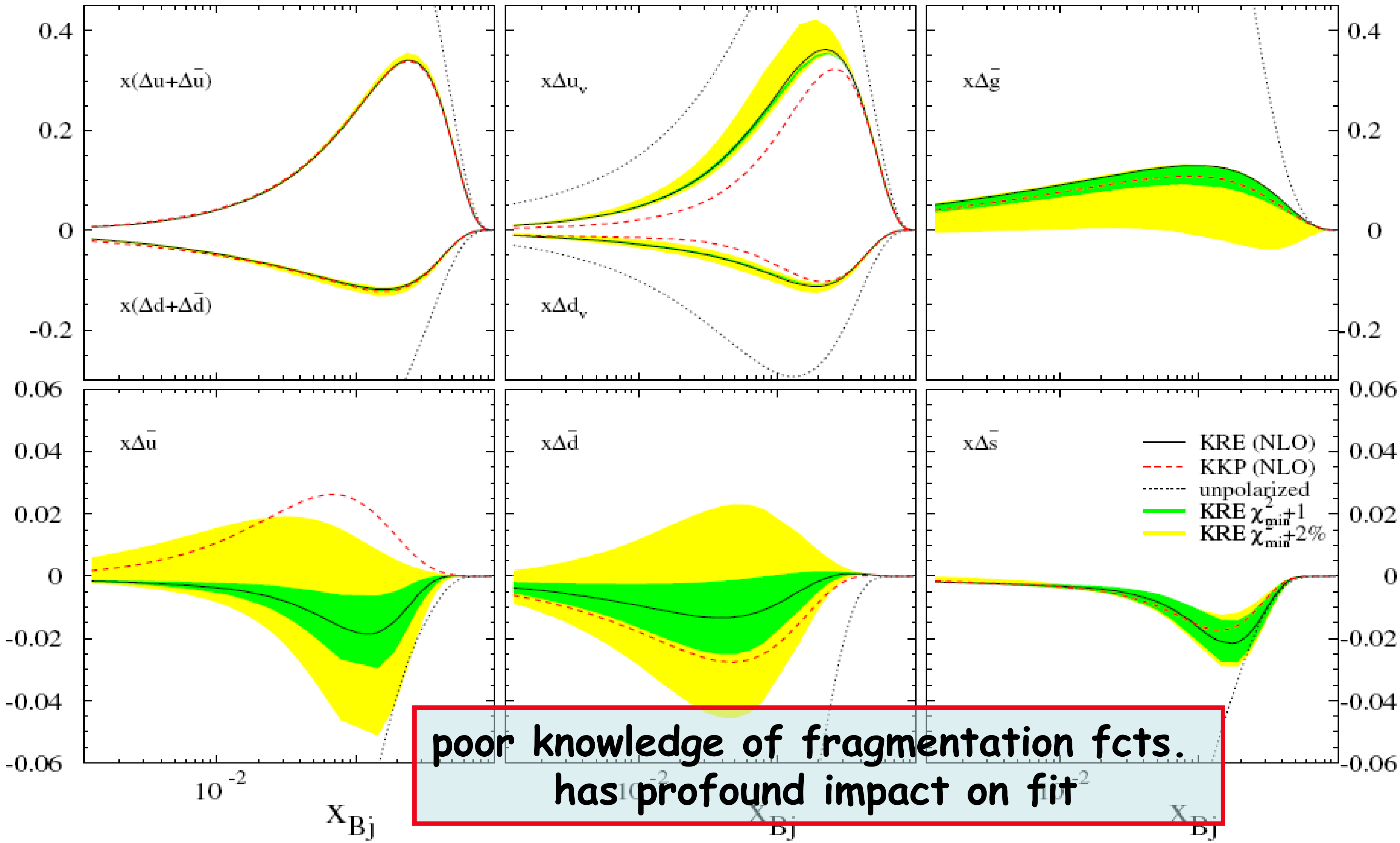
$\rightarrow$ **Δg positive at large-x**

$\int_{0.1}^{1} \Delta g(x)\,dx \simeq 0.3 \pm 0.35$

tension gone in latest data sets
conclusion for Δg ?

Sassot et al. DIS+SIDIS fit

- full NLO global analysis of DIS + SIDIS data plus study of A_{LL} (pions)

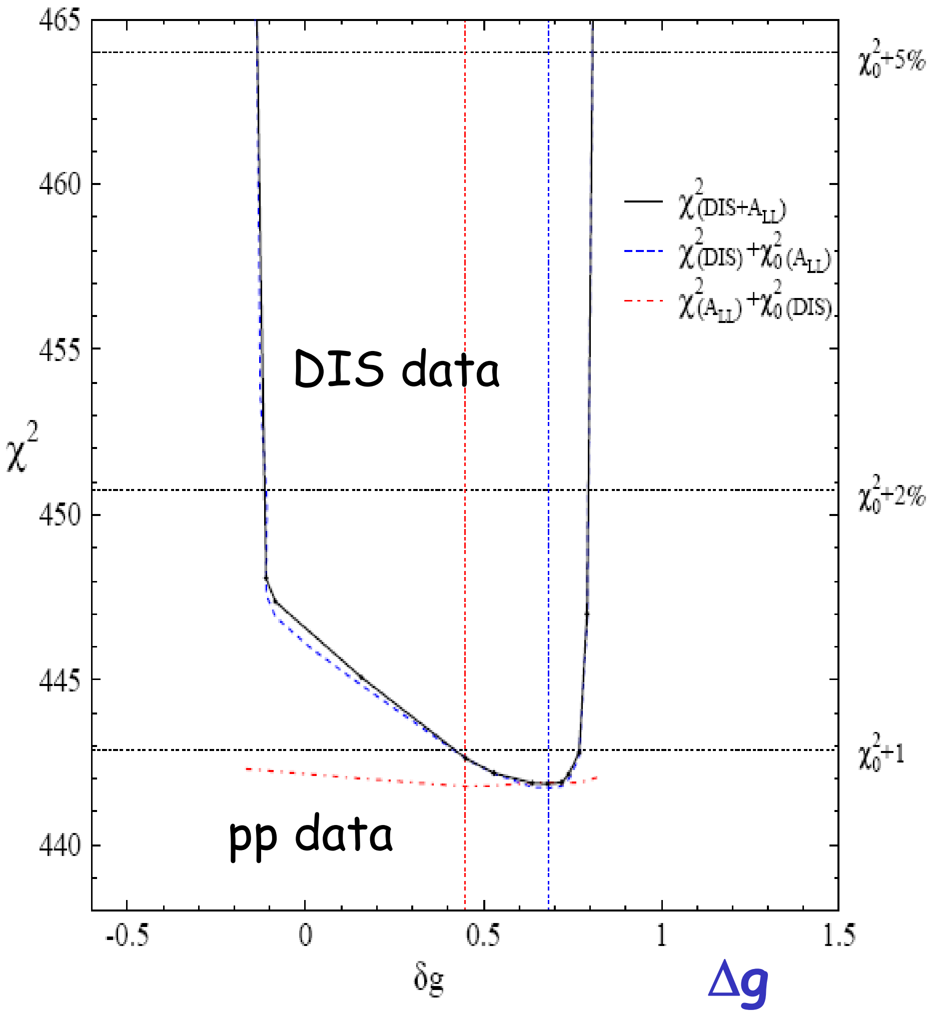


poor knowledge of fragmentation fcts.
has profound impact on fit

- **full flavor separation** from SIDIS (compatible with an SU(3) sym. sea)
- pdf uncertainties from Lagrange multiplier method

$$\Phi(\lambda_i, a_j) = \chi^2(a_j) + \sum_i \lambda_i O_i(a_j)$$

use $\Delta\chi^2$ = 1 or 2 (5) % variation



find:

- $\int_0^1 \Delta g(x, 10\,\mathrm{GeV}^2) = -0.107 \div 0.807$

  (for a 2% variation in χ^2)

- **from DIS/SIDIS alone: $\Delta g \gtrsim 0$**

  run-5 pp pion data:

  consistent but no extra constraint

  different from AAC, GRSV

- **χ^2 profiles are not parabolic**

  $\rightarrow$ invalidates Hessian method

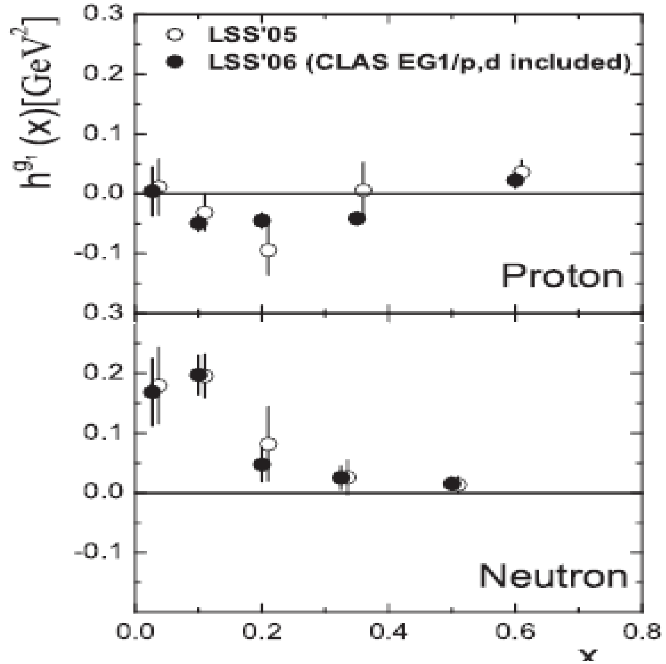
LSS DIS fit

Leader, Sidorov, Stamenov

- incl. latest DIS data
- *assume* SU(3) symmetric sea
- "home-made" g_1 data

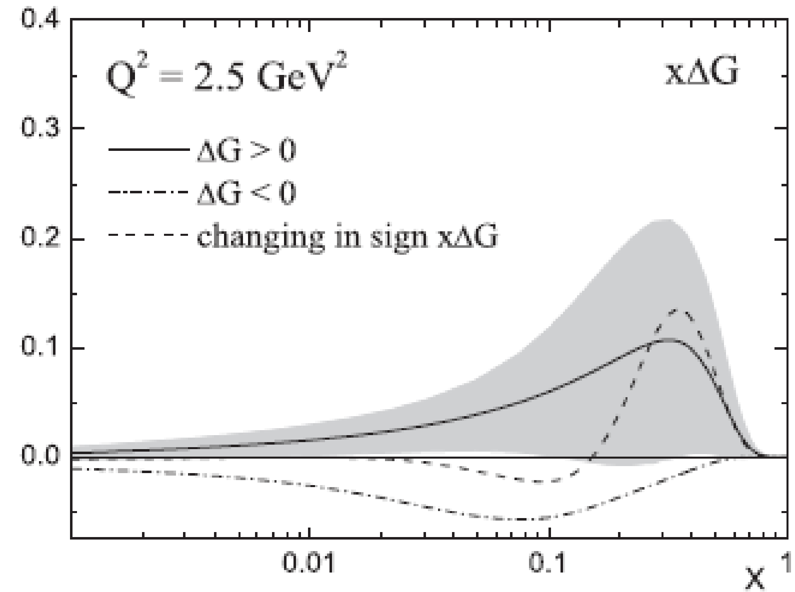
$$\frac{g_1(x,Q^2)|_{LT} + h(x)/Q^2}{F_1(F_2,R)|_{exp}}$$

$\rightarrow$ fit of higher twist



mainly driven by CLAS data

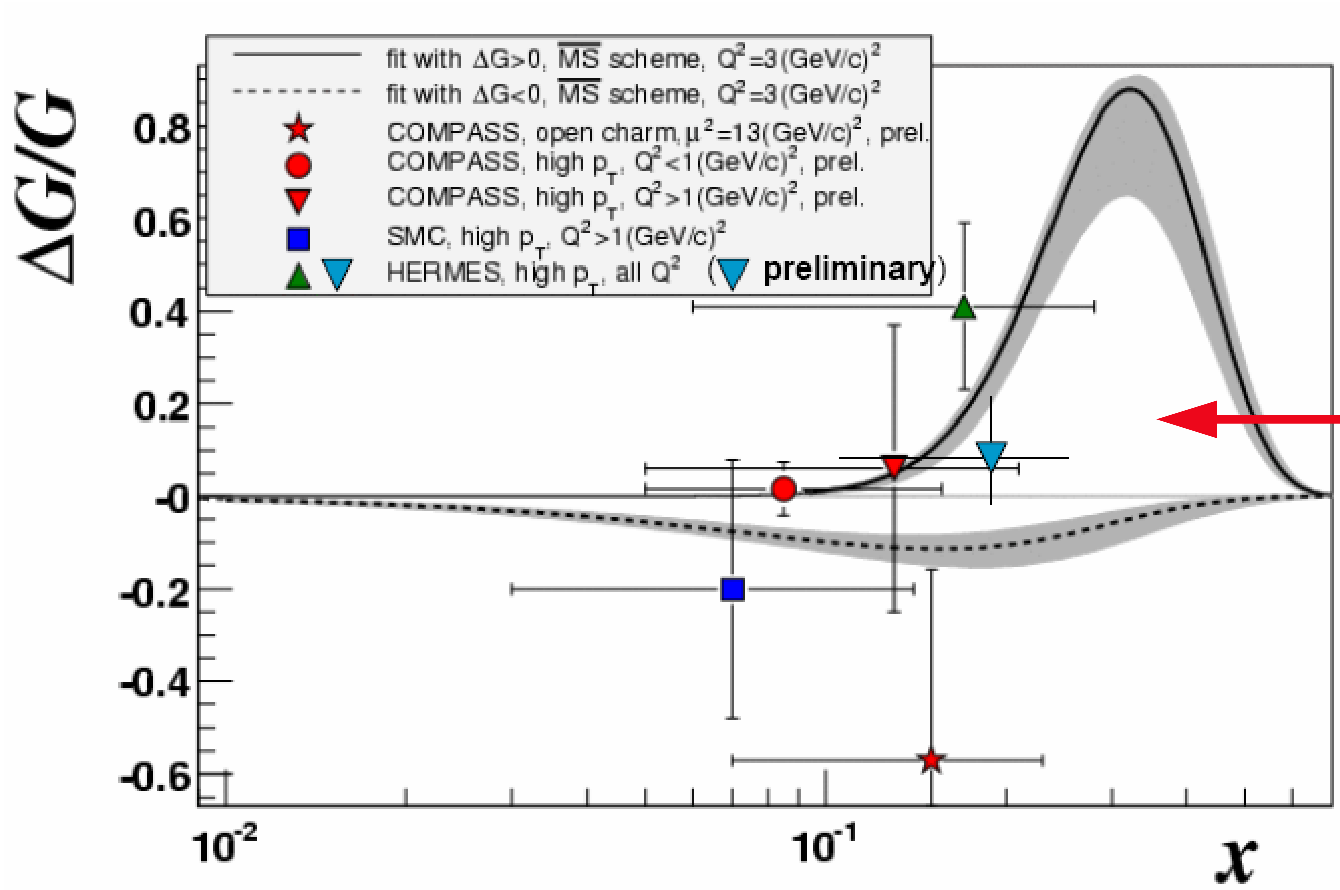
- error analysis (Hessian ??)
  incl. stat.+sys.; bands for $\Delta\chi^2$=1 (?)
- before 2006:
  Δg *positive* with *small* errors
- latest analysis:
  sign now undetermined; possible node
  find small $\int_0^1 |\Delta g(x)|\, dx \simeq 0.3$



COMPASS DIS fit

- based on latest DIS data
- set-up similar to old SMC QCD fit
- two "solutions" for Δg with *very* small errors

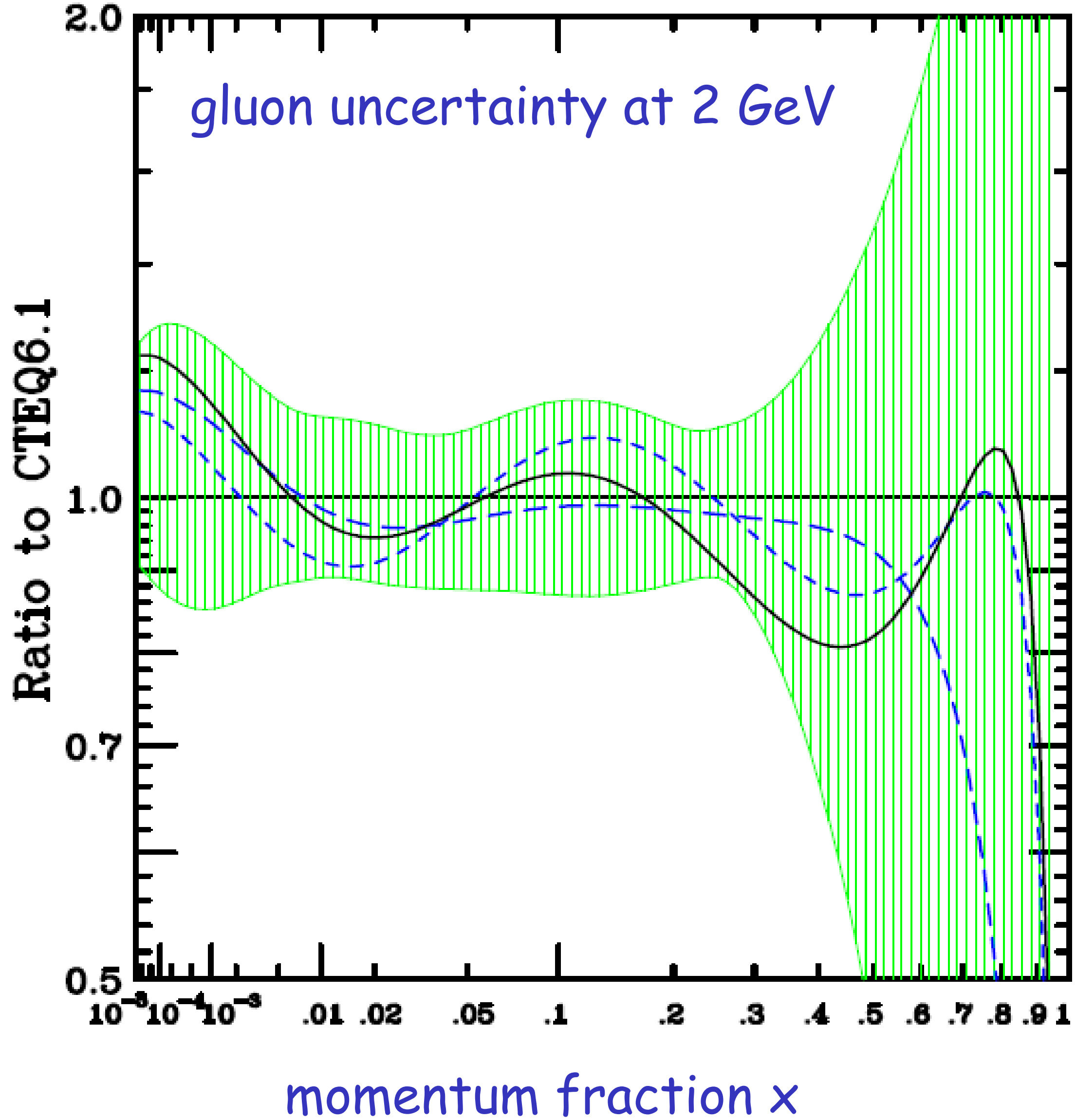
"warning":
in global analyses
$\Delta\chi=1$ does not reflect
"real" errors (CTEQ, ...)
$\Delta\chi^2=1\div2\%$ more realistic



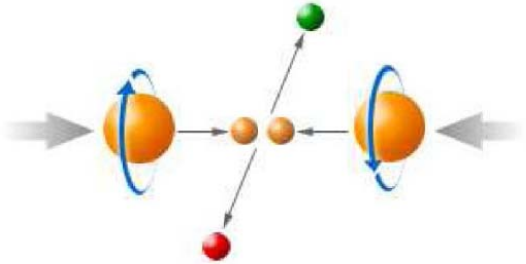
What about all the Δg's in between ??

$\Delta g/g \to \Delta g$??

latest CTEQ analysis hep-ph/0611245



one should not forget the large uncertainties in the *unpolarized* gluon distribution at large x towards a global analysis of polarized parton densities



$\approx$ 20 years of experience in analyzing unpolarized data:

DFLM, ... , GRV, MT, MRS, ... , MSTW, CTEQ, ...

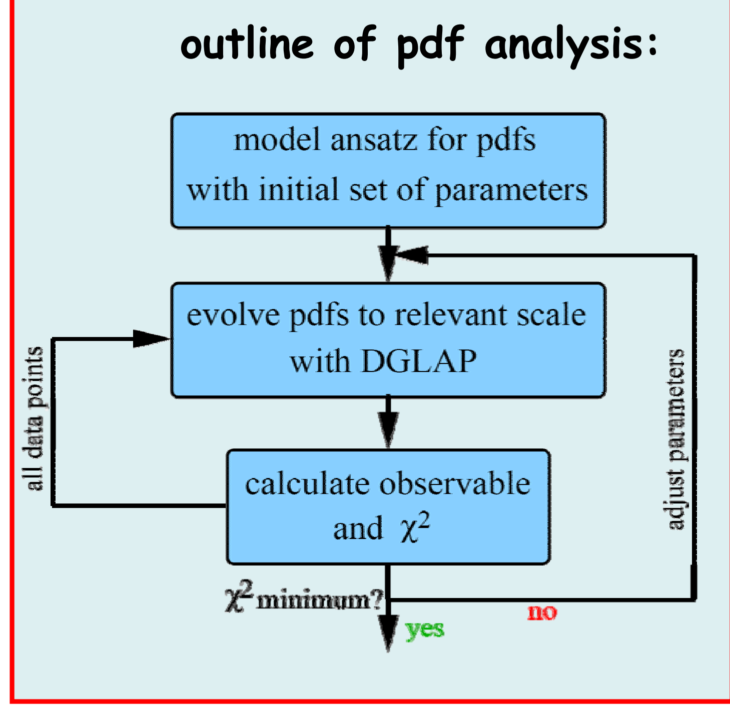
learning about nucleon structure requires a global QCD analysis

even more true for the spin structure

due to lack of “HERA-like” DIS data

none of the current analyses is a full global analysis

global analysis



unpolarized pdfs: CTEQ, MRST

- gluon constrained by scaling-violations
- 2^{nd} moment constrained (mom. sum)
- pp data only for fine-tuning pdfs

K-factor approx., etc. often reasonable

polarized pdfs: *completely different situation!*

- gluon largely unconstrained by existing DIS data
- no momentum sum rule; pol. pdfs can have nodes
- pp data determine Δg and other aspects of pdfs

full NLO global analysis mandatory; no approximations

MS, Vogelsang

a way to do it: Mellin technique

earlier ideas: Berger, Graudenz, Hampel, Vogt; Kosower

goal: handle exact NLO expressions in a fast global χ^2 analysis

idea: use Mellin n-moments to get rid of slow multi-convolutions

$$h^n \equiv \int_0^1 dx\, x^{n-1}\, h(x) \xrightarrow[\text{factorize}]{\text{convolutions}} (g \otimes h)^n = g^n\, h^n$$

example: pp$\to \pi$ X

$$d\Delta\sigma = \sum_{abc} \int \Delta f_a\, \Delta f_b\, d\Delta\hat{\sigma}_{ab\to cX}\, D_c\, dx_a dx_b dz_c$$

express pdfs by their Mellin inverses

$$\frac{1}{2\pi i}\int_{C_n} dn\, x_a^{-n}\, \Delta f_a^n \qquad \frac{1}{2\pi i}\int_{C_m} dm\, x_b^{-m}\, \Delta f_b^m$$

$$= \frac{1}{(2\pi i)^2} \sum_{abc} \underbrace{\int_{C_n} dn \int_{C_m} dm}_{\text{standard Mellin inverse}} \underbrace{\Delta f_a^n \Delta f_b^m}_{\text{fit}} \underbrace{\int x_a^{-n} x_b^{-m} d\Delta\hat{\sigma}_{ab\to cX}\, D_c\, dx_a dx_b dz_c}_{\equiv\, d\Delta\tilde{\sigma}_{ab\to cX}(n,m)}$$

can be pre-calculated on grids!

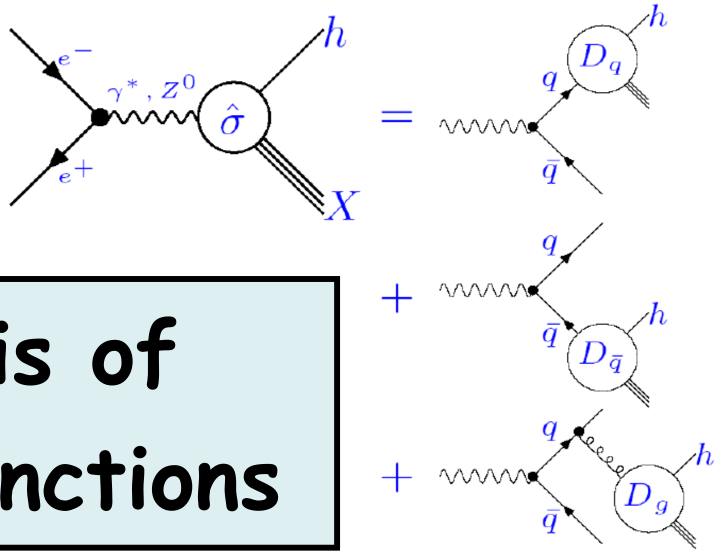
with latest data from RHIC a

global analysis starts to make sense ...

the work just started ...

D. de Florian, R. Sassot, MS, W. Vogelsang

in the long-run a CTEQ-like collaboration is desirable



1st global QCD analysis of fragmentation functions

(also an important stress test of the Mellin technique !!)

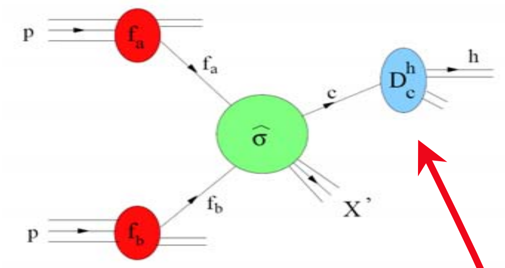
in collaboration with
D. de Florian & R. Sassot
hep-ph/0703242 (PRD)

precise knowledge of fragmentation functions crucial for interpretation & understanding of RHIC results and QCD in general

unpolarized pp cross sections are an important baseline for

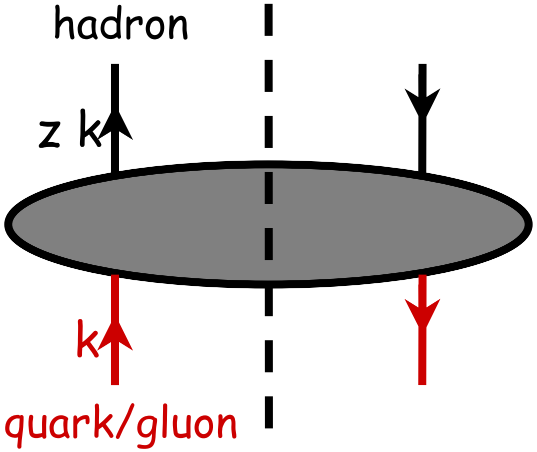
- studies of saturation effects in dAu and AuAu collisions
- our understanding of A_{LL} and the extraction of, e.g., Δg

RHIC also puts fundamental ideas to the test



- fragmentation as fundamental as nucleon structure
- factorization and universality of fragmentation functions

some properties of D(z,μ)



- non-perturbative ***universal*** objects
  scale μ-dep. predicted by pQCD

- needed to consistently absorb final-state collinear singularities like, e.g., in $pp \to \pi^0 X$ ("***factorization***")

- describe the *collinear* transition of a massless parton "i" into a massless hadron "h" carrying fractional momentum z

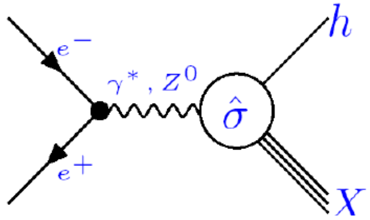
- bi-local operator: $D(z) \simeq \int dy^- e^{iP^+/zy^-} \mathrm{Tr}\gamma^+ \langle 0|\, \psi(y^-) |hX\rangle \langle hX| \overline{\psi}(0)\, |0\rangle$

  Collins, Soper '81, '83

no inclusive final-state
$\to$ no local OPE $\to$ no lattice formulation

previous analyses

Kretzer; Kniehl et al.; Hirai et al.



- based only on e^+e^- annihilation data from LEP
- many shortcomings

results of analyses differ wildly, at scales μ relevant for RHIC

- gluon fragmentation ??
- flavor separation ??

often trouble in describing pp and ep hadron data

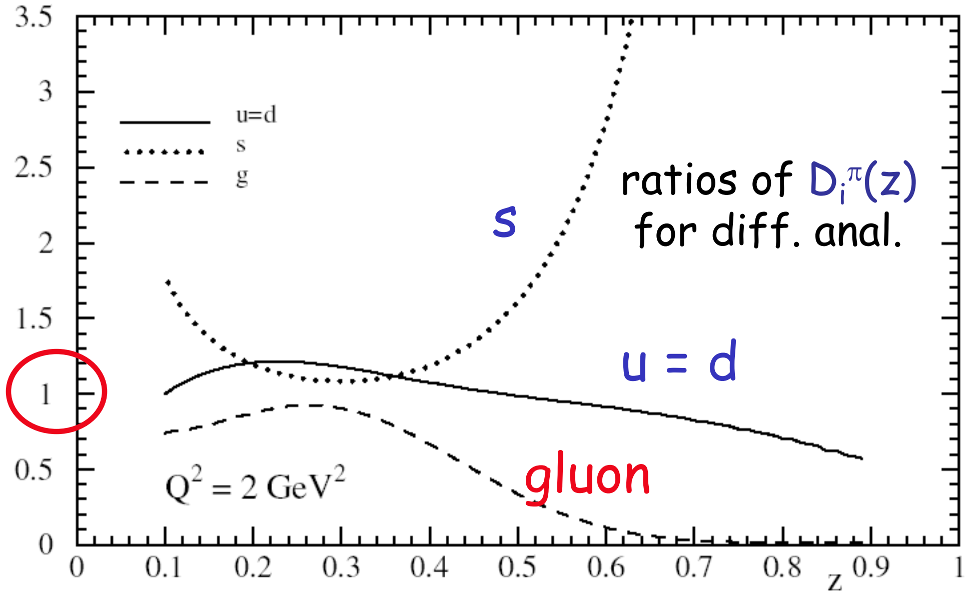


fig. by S. Kretzer

key question:

can we arrive at a global description of all e^+e^-, ep, and pp data in terms of a *universal set* of fragmentation functions?

new analysis collaboration formed:

D. de Florian,
R. Sassot, MS

goal: provide NLO (and LO) D_i^h for $\pi^\pm$ ✓, $K^\pm$ ✓, p, $h^\pm$, Λ , η , ...

and estimate their uncertainties

prel. results

analysis setup:

use technology spin-offs & experience from pdf analyses

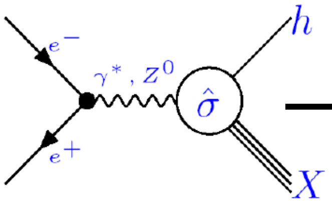
- "Mellin technique" to handle exact NLO expressions in fits
- "Lagrange multiplier" technique to estimate uncertainties
- fast & well-tested DGLAP evolution codes
- vast array of NLO calculations for ep and pp at hand

- o input scale for evolution: μ = 1 GeV
- o $D_i(z,\mu) = N\, z^\alpha (1-z)^\beta [1 + \gamma\,(1-z)^\delta]$ for i = u,d,s; i = g, c, b w/o [...], allow for small isospin violations
- o fit exp. normalizations within quoted uncertainties

Σ: 23 parameters

global analysis includes

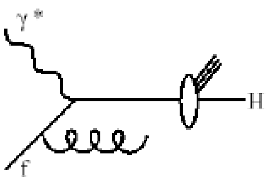
- **e^+e^- annihilation data** (as in all previous analyses a la AKK, KKP, Kretzer)



$\longrightarrow$ normalized distribution $\frac{1}{\sigma_{tot}} \frac{d\sigma^h}{dz}$ where $z \equiv \frac{2P^h \cdot q}{Q^2} = \frac{2E^h}{Q}$

precise data at $Q=M_Z \rightarrow$ **D_Σ well determined; D_g weakly constrained**

- **ep semi-incl. DIS hadron multiplicities** (new)



$$\longrightarrow \quad \frac{d\sigma^h}{dx dQ^2 dz^h} \approx \sum_{f=q,\bar{q}} e_f^2 f(x,\mu_f) D_f^h(z^h,\mu_f') + \mathcal{O}(\alpha_s)$$

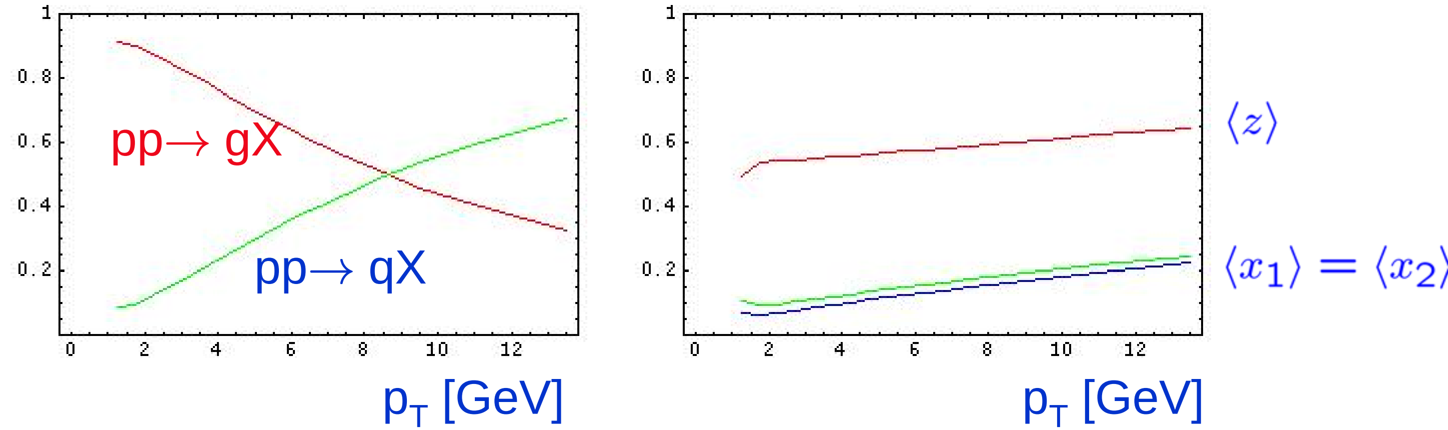
data for π^+, π^-, K^+, K^-, ... $\rightarrow$ **flavor separation** possible

- **pp hadron production data** (new)

data from CERN-SPS, TeVatron, RHIC $\rightarrow$ **D_g and flavor separation**

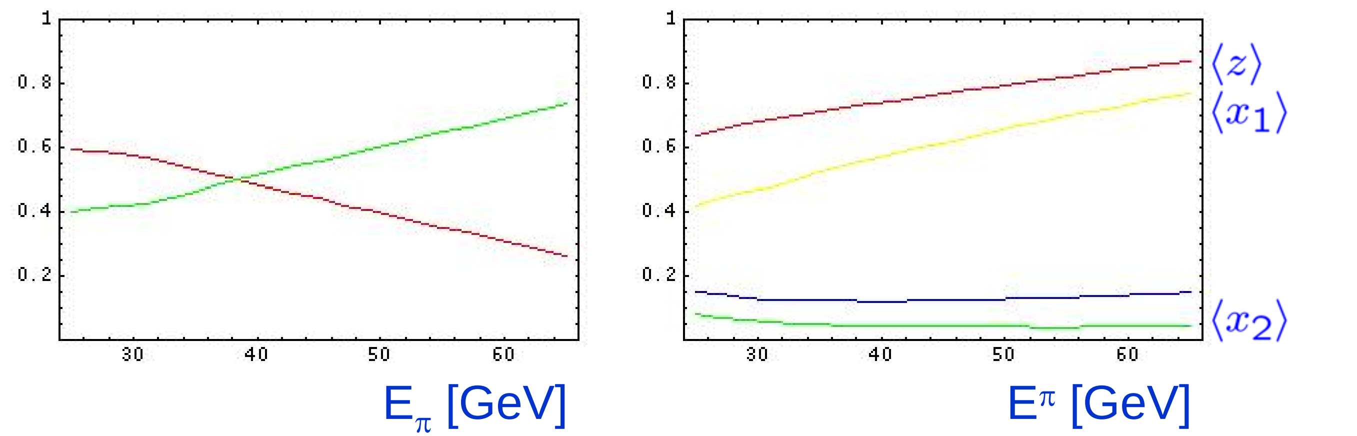
relevance of RHIC pp $\to$ hX data

central rapidity



$\to$ low p_T data probe gluon fragmentation

forward rapidity



$\to$ probe gluon and quark fragmentation at large z

BRAHMS $\pi^\pm$, $K^\pm$ data ($\eta \simeq 3$) $\to$ flavor separation from pp data as for all previous analyses:

untagged & flavor tagged

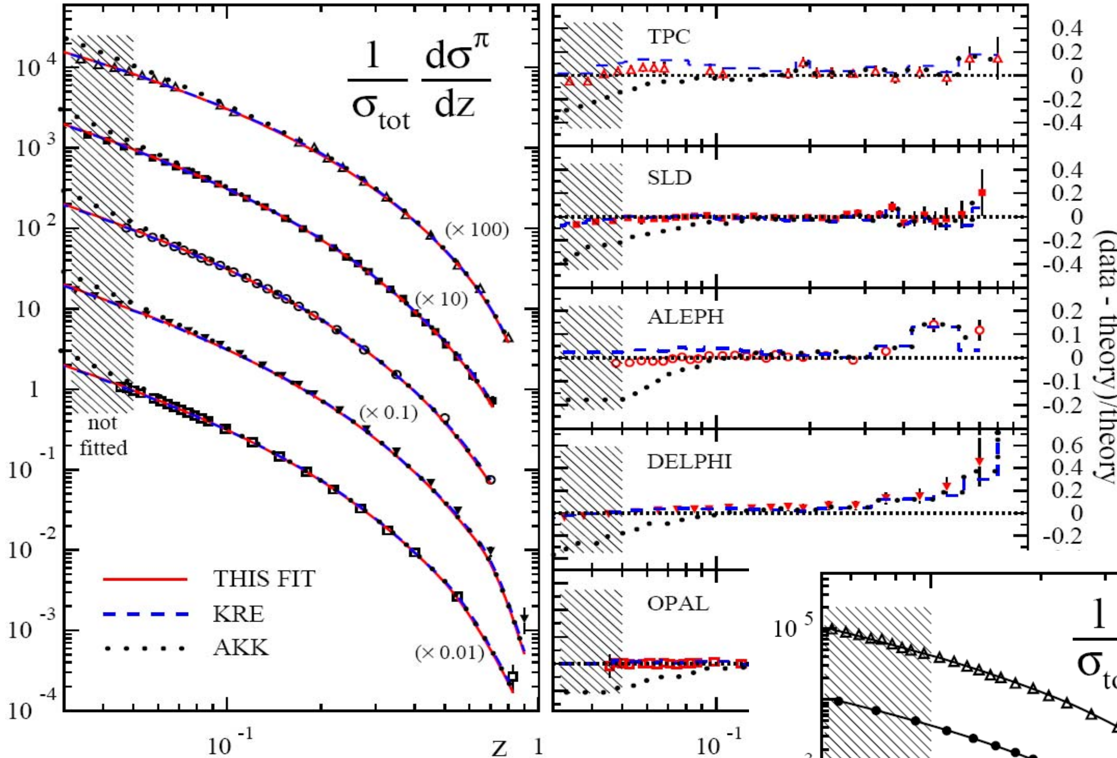
excellent description of all e^+e^- data

for pions, kaons, protons, charged hadrons

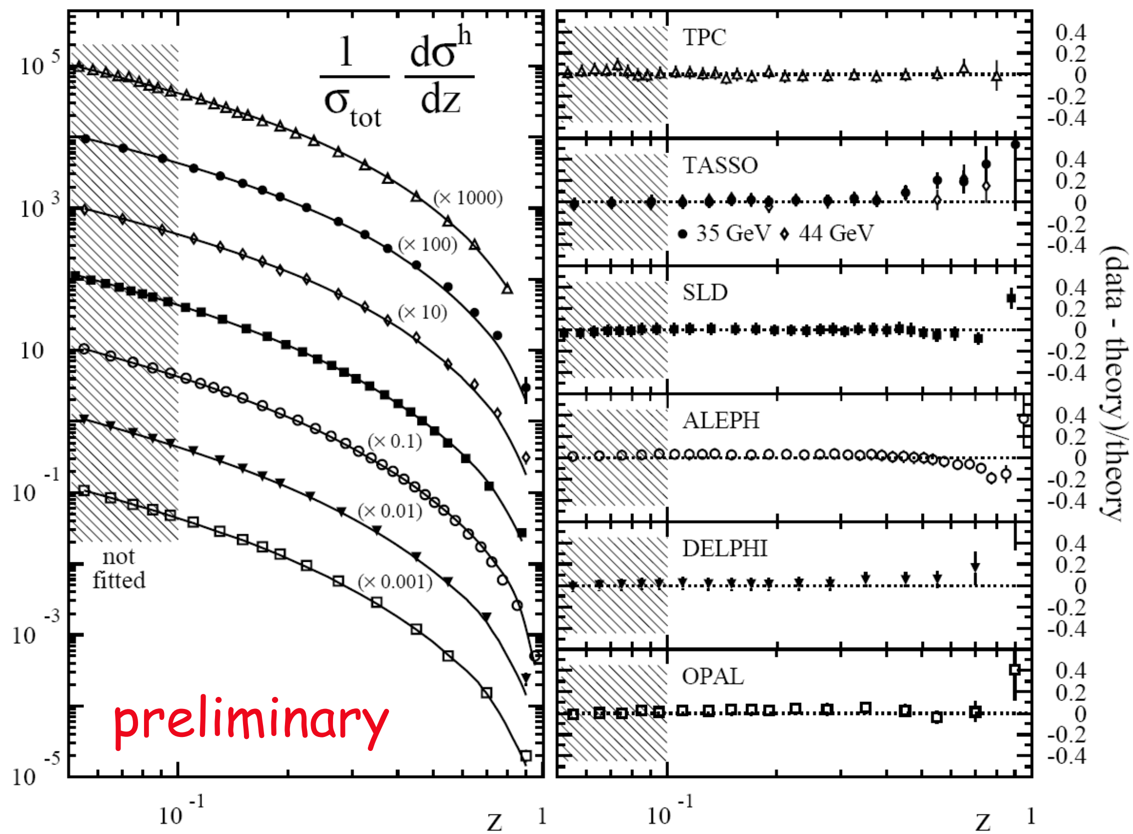
published

sneak preview
(to be published soon)

pions



charged hadrons



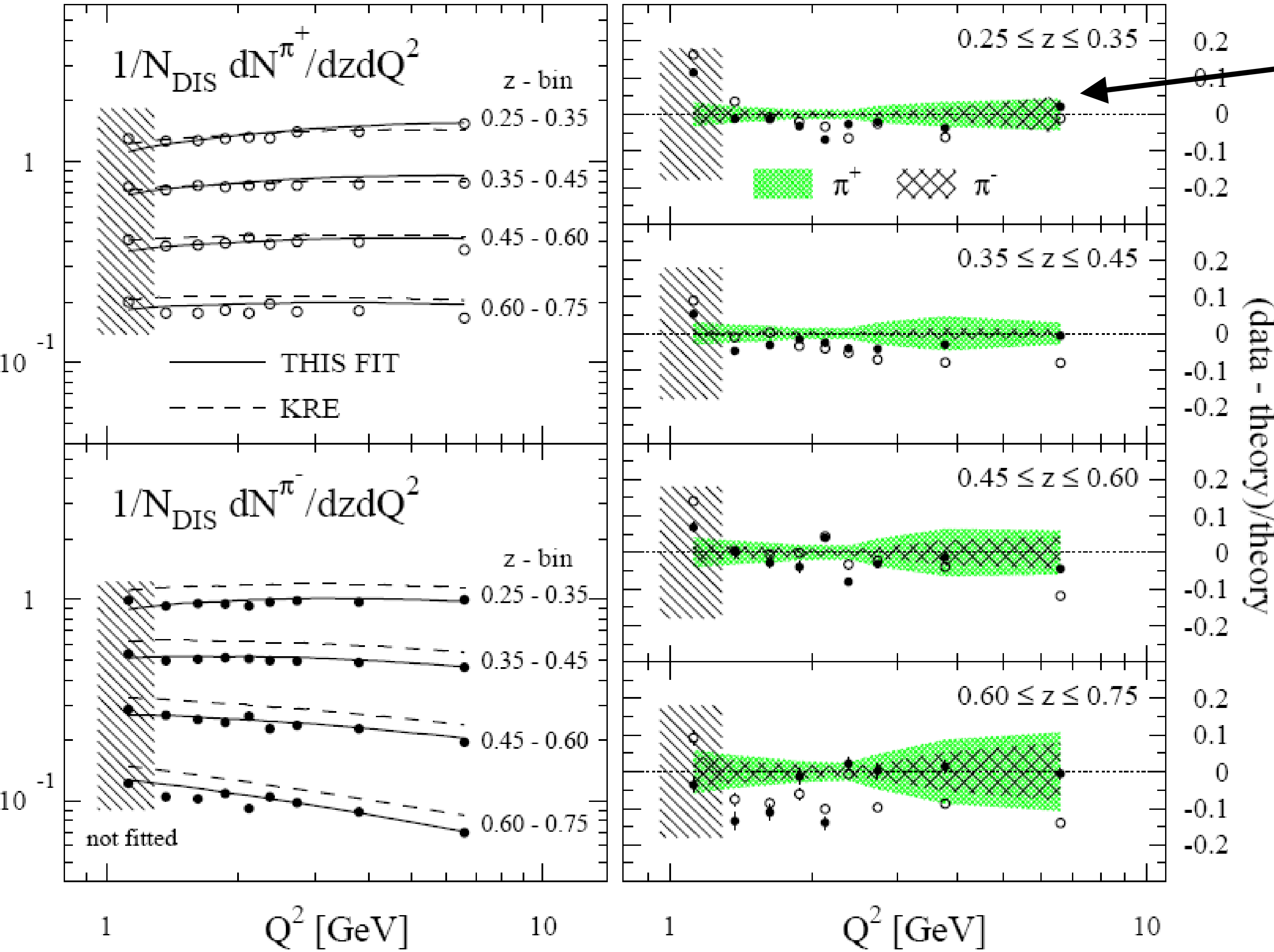
beyond that:

good global description of all ep and pp data

some examples ...

HERMES $\pi^\pm$ multiplicities

similarly for HERMES $K^\pm$ and EMC $h^\pm$ data



shaded bands: our estimate of "Q^2-bin effects"

previous fits:

KKP, AKK: of no use! (no charge sep.)

Kretzer:

$\pi^\pm$, $h^\pm$ O.K.

$K^\pm$ bad descrip.

some comparisons with RHIC data

STAR forward pions

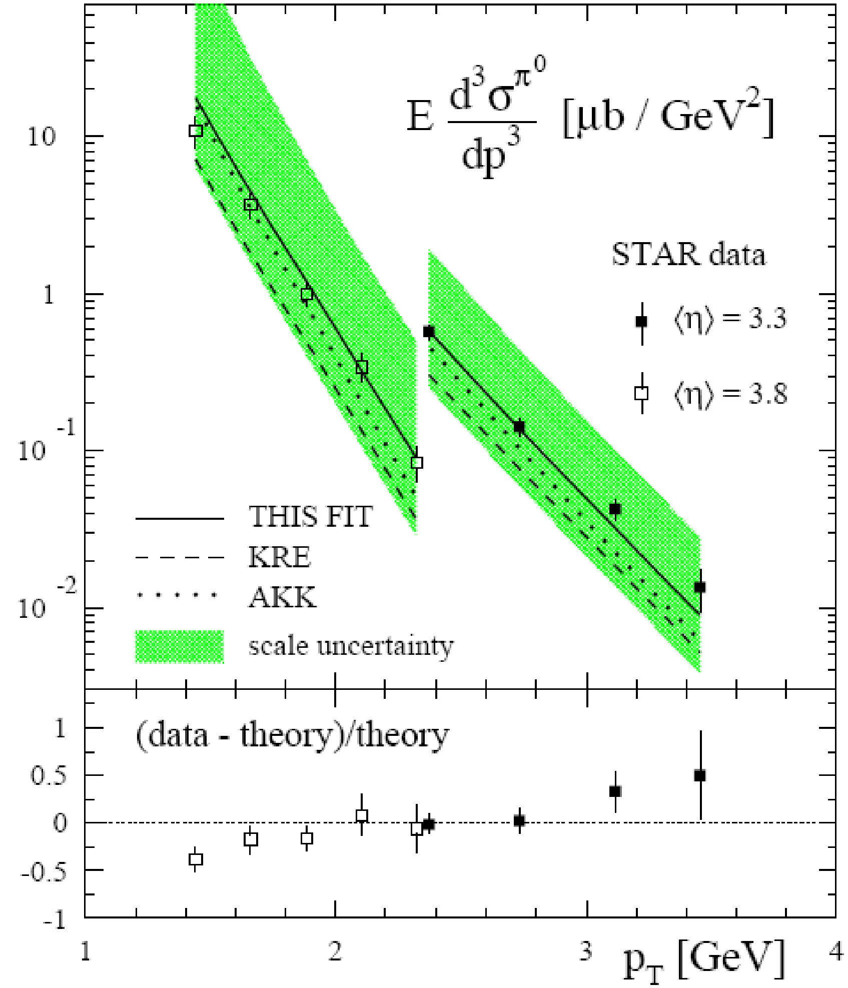
general trend for all pp (and $p\bar{p}$) data:

all data described by scale choice $\mu = p_T$

scale uncertainties are very sizable

"Kretzer" always too low for $\mu = p_T$

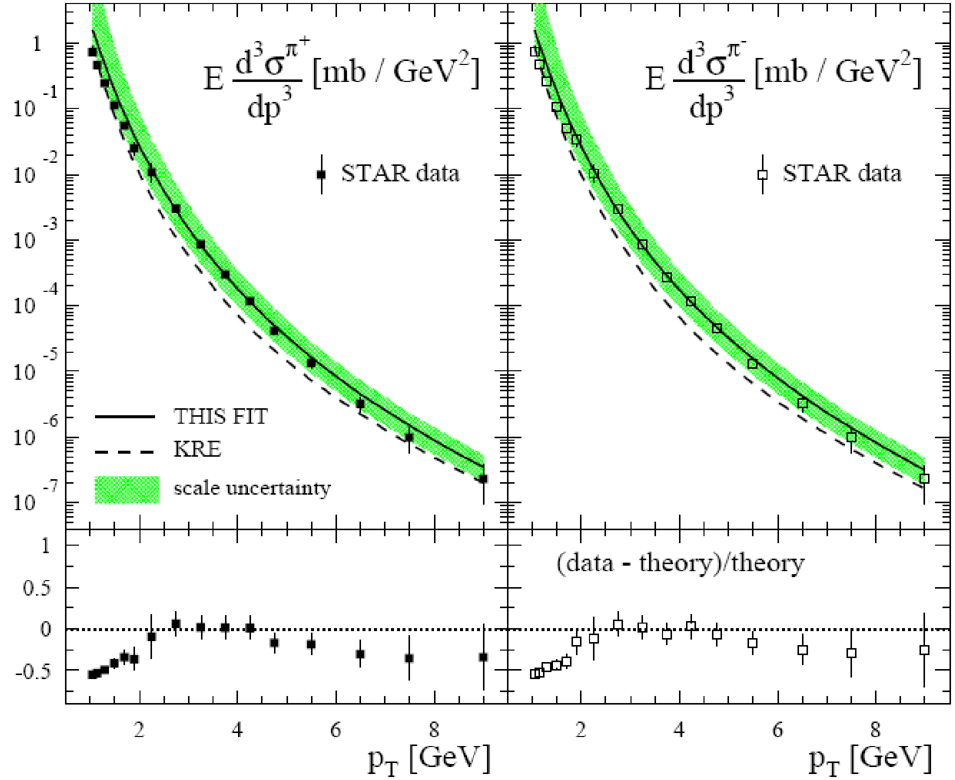
some data sets are mutally contradictory
(mainly some UA1 data sets for $h^{\pm}$)

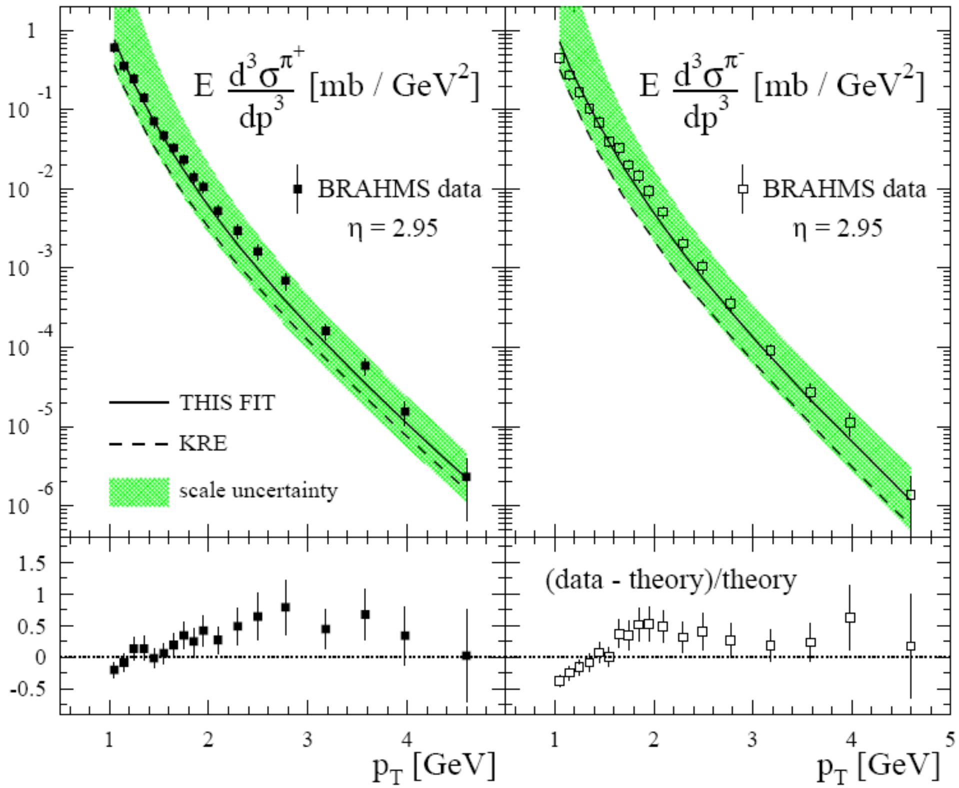


charge separated $\pi^{\pm}$

STAR

central rapidities





BRAHMS

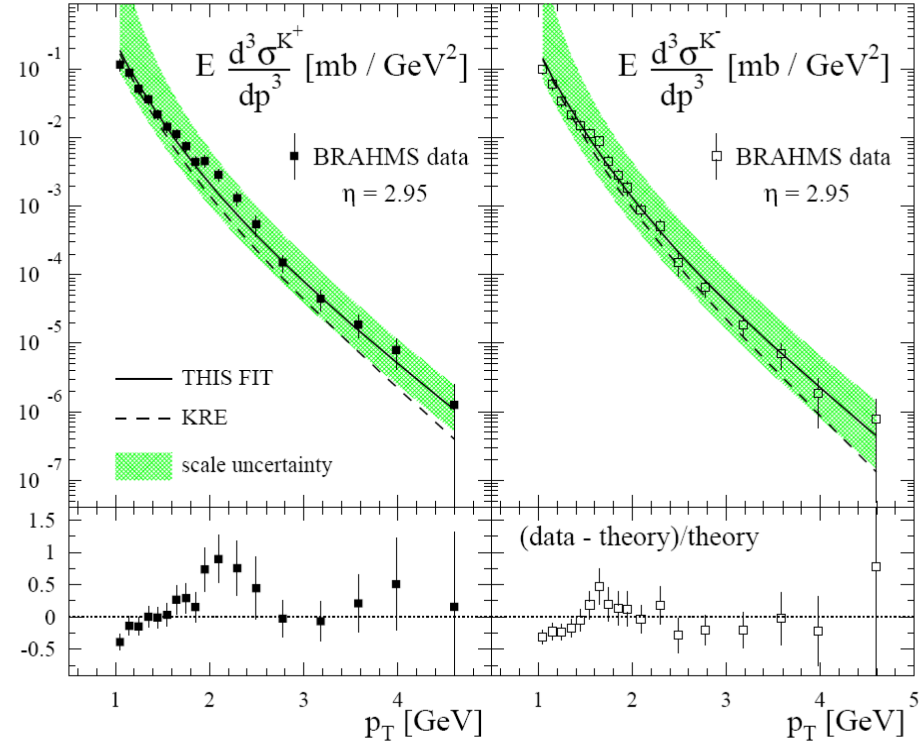
forward rapidities

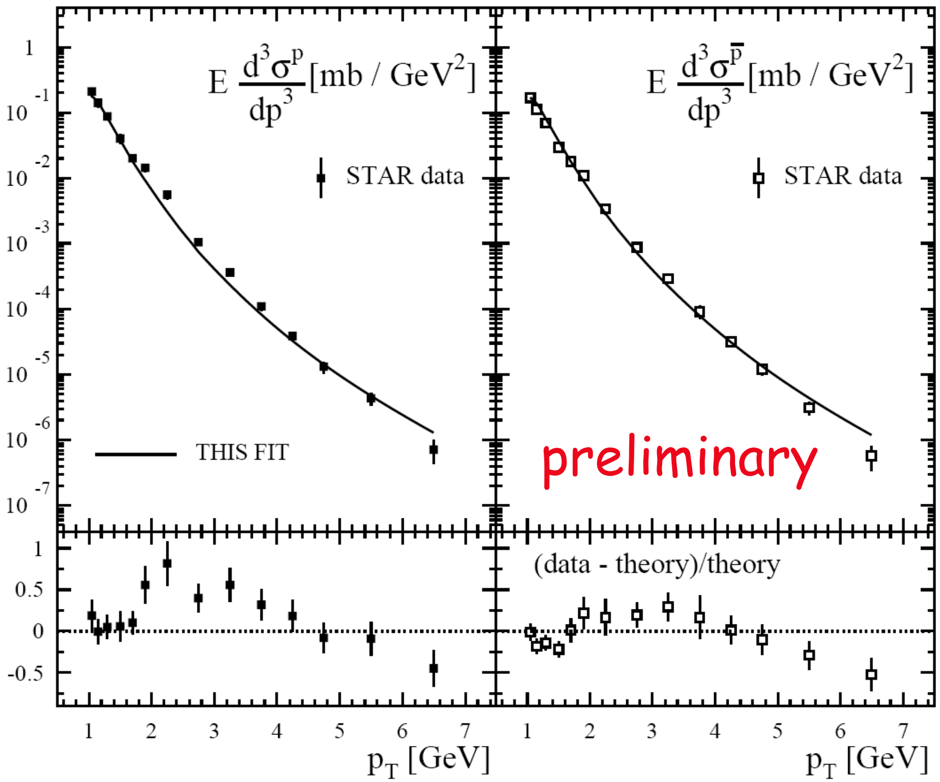
charge separated data

$K^{\pm}$

BRAHMS

forward rapidities





STAR

central rapidities

$p, \bar{p}$

what have we learned?

important test of universality and factorization *plus*

much reduced uncertainties thanks to pp and ep data!

two methods to explore uncertainties:

pioneering work by CTEQ collaboration

- **"Hessian method"** $[\delta D]^2 = \Delta\chi^2 \sum_{ij} \frac{\partial D}{\partial a_i} H_{ij}^{-1} \frac{\partial D}{\partial a_j}$

  assumes that χ^2-profile is quadratic in all parameters a_i; uncertainties propagate linearly to observables

  not always reliable!

- **"Lagrange multiplier method"** $\Phi(\lambda_i, a_j) = \chi^2(a_j) + \sum_i \lambda_i O_i(a_j)$

  probes uncertainties in observables O_i *directly*, straightforward to implement

  steps: minimize for $\lambda_i = 0 \rightarrow$ "best fit" with χ_0^2, parameters $a_j^0, O_i(a_j^0)$

  explore χ^2-profile for various fixed $\lambda_i \neq 0$ (=force values of O_i)

  ideal case: parabolic profiles, $\Delta\chi^2$=1 for 1σ errors

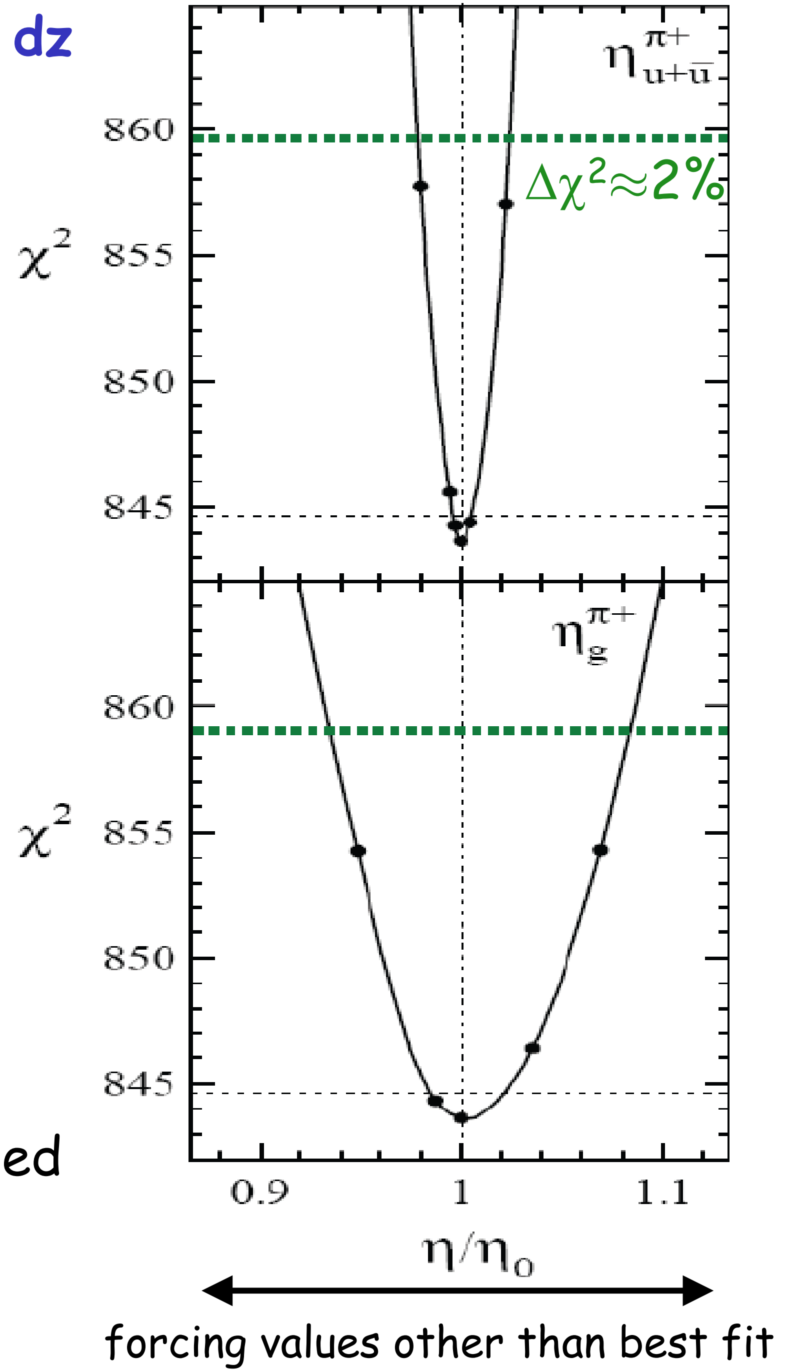
  in practice: unaccounted errors, $\Delta\chi^2$= 1 - 2% more appropriate

χ^2 - profiles for

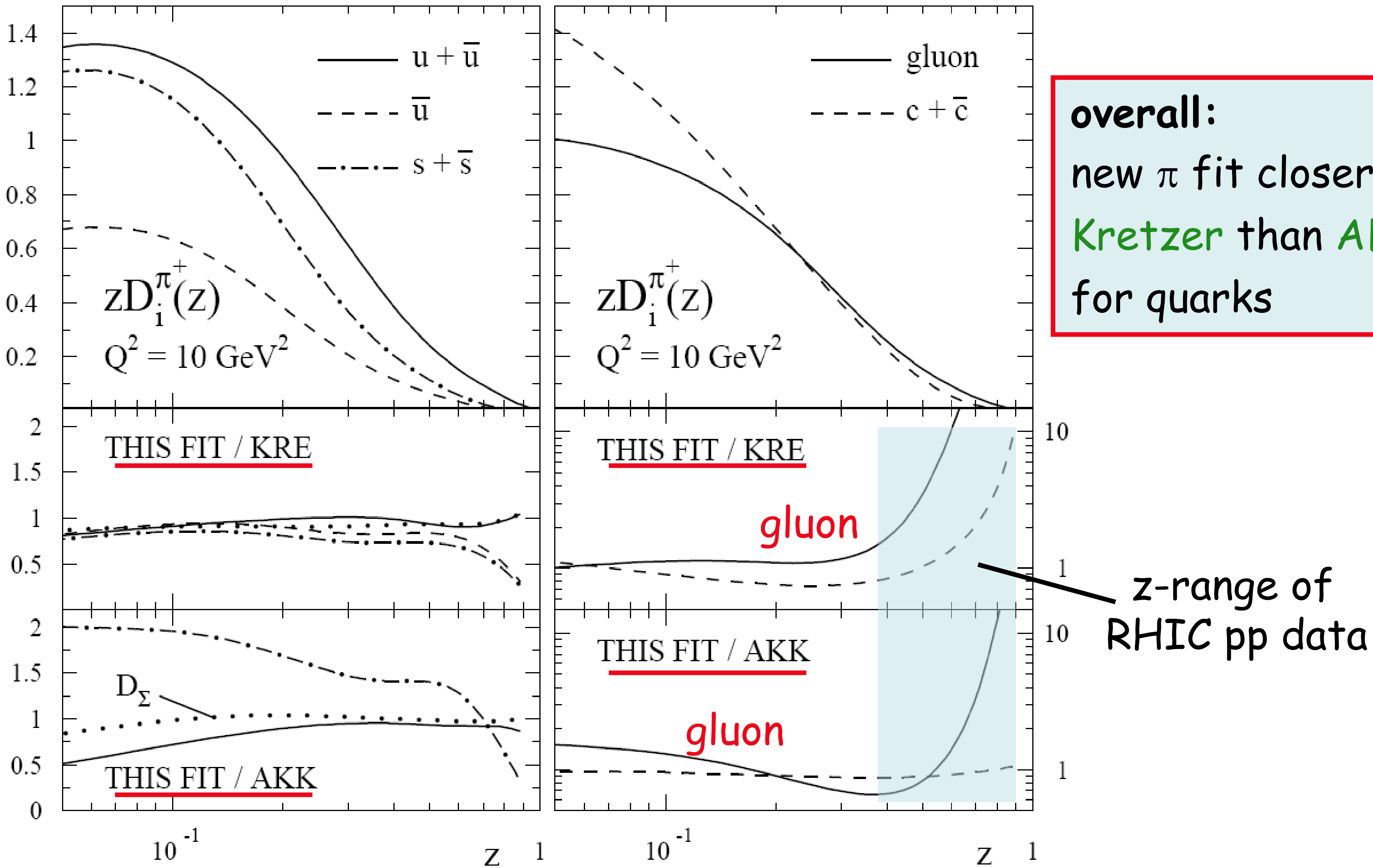
$\eta_i = \int_{0.2}^{1} z\, D_i(z,\mu)\, dz$
$\mu = 5$ GeV

we find: (using $\Delta\chi^2 \approx 2\%$)

- $u_{tot} \rightarrow \pi^+$ constrained best
  about 3% uncertainty
  e^+e^- data alone do a good job
- $g \rightarrow \pi^+$ uncertainty $\approx$ 8%
  much weaker constraint
  from using only e^+e^- ($\approx$20%)
- complementary information from different processes always leads to well defined minima
- kaon fragmentation is less well determined



comparison with KRE & AKK



overall:

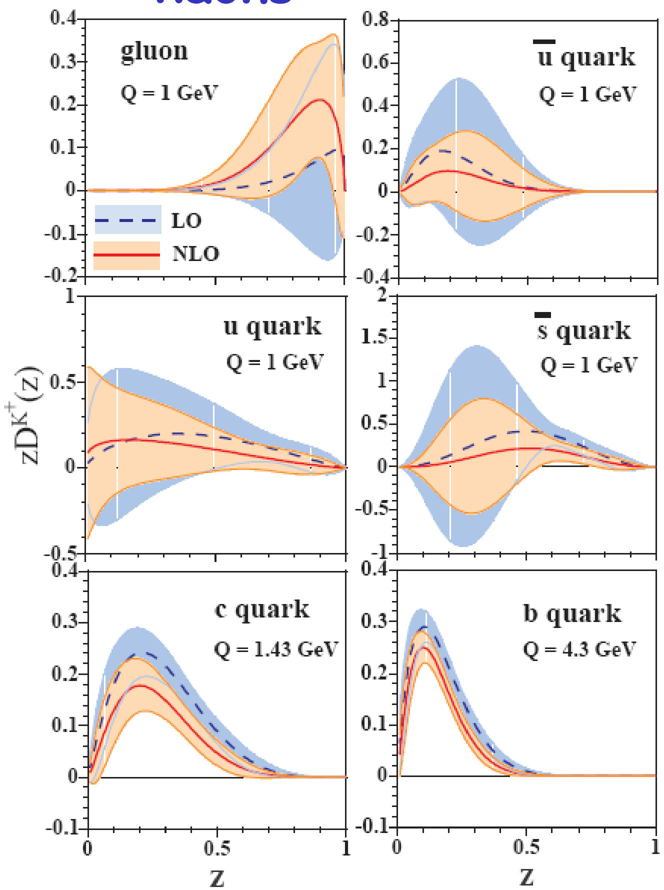
new π fit closer to Kretzer than AKK for quarks

recent e^+e^- analysis

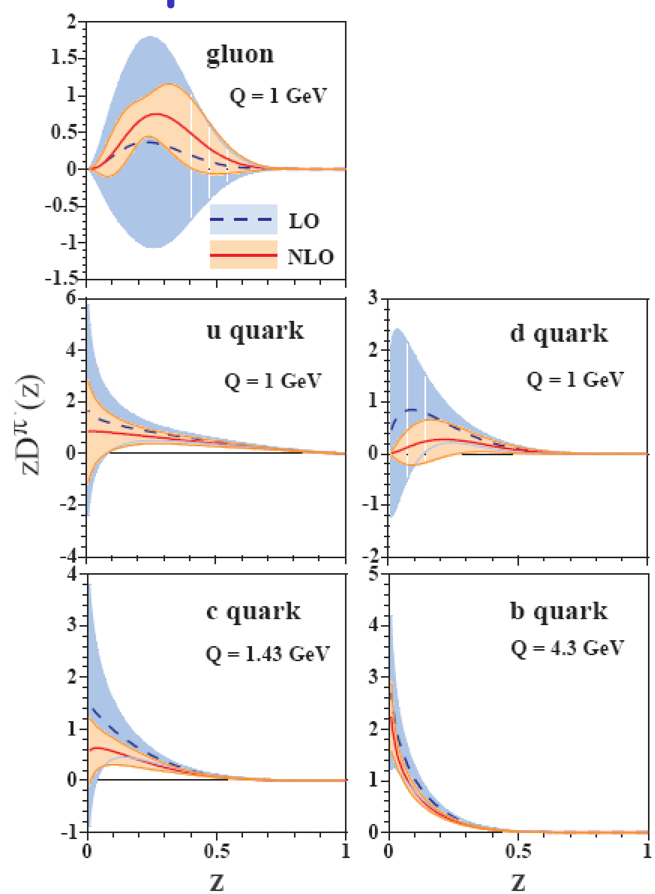
Hirai, Kumano,
Nagai, Sudoh
PRD75(2007)094009

pions, kaons and protons analyzed; uncertainties estimated with Hessian method

kaons



pions



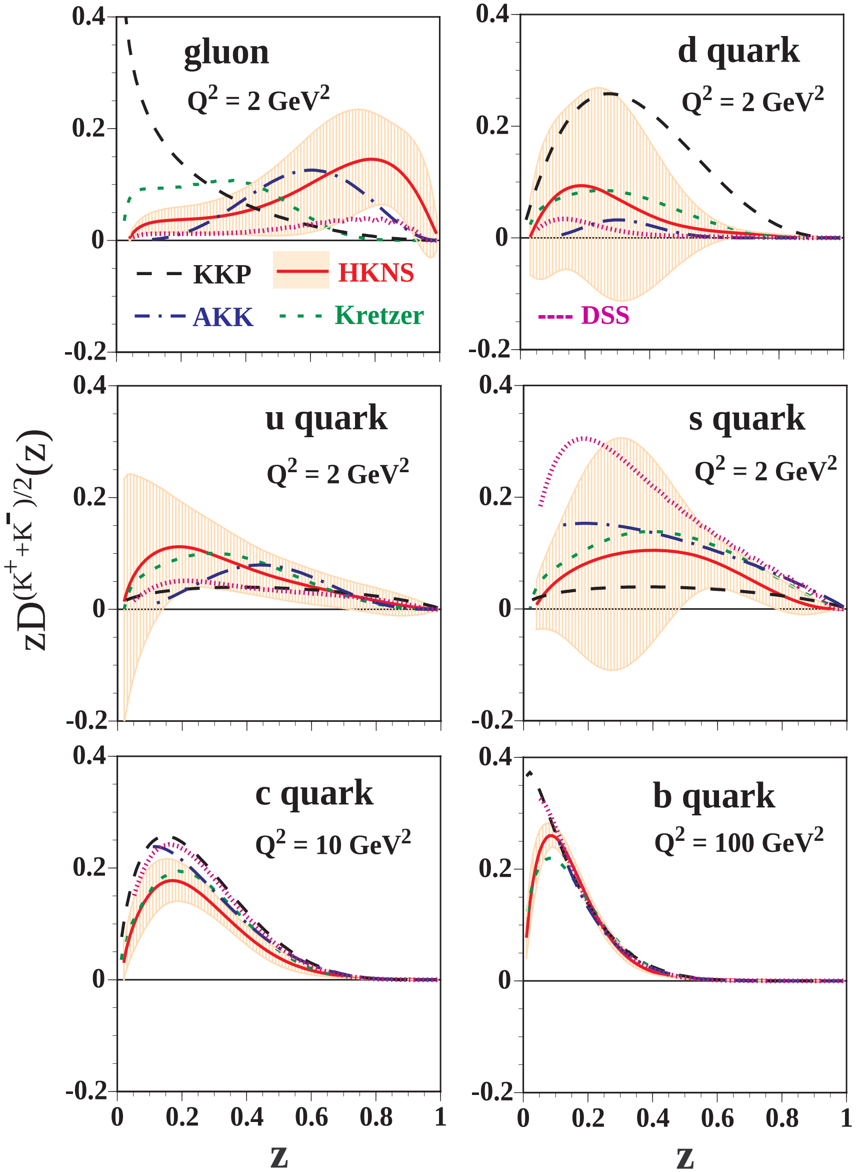
important step:

- quantifies uncertainty known from comparing xKK with "Kretzer"
- **but** errors extend to unphysical region $\rightarrow$ neg. pp cross sec.??
- D_g^{π} looks small $\rightarrow$ RHIC pp data ??
- *assumes* sym. sea D^{π}_{sea}

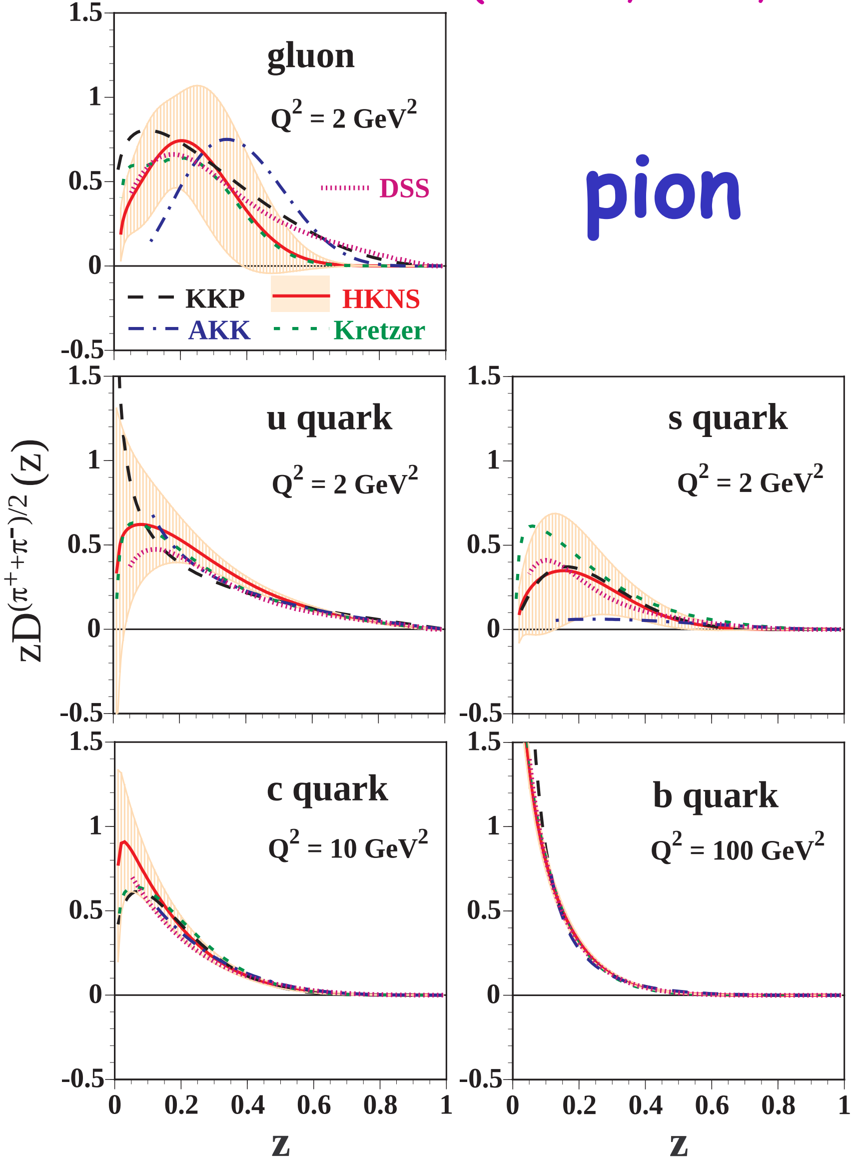
comparison (by K. Sudoh)

HKNS (Hirai, Kumano, Nagai, Sudoh)
Kretzer
KKP (Kniehl, Kramer, Potter)
AKK (Albino, Kniehl, Kramer)
DSS (deFlorian, Sassot, Stratmann)

kaon



pion



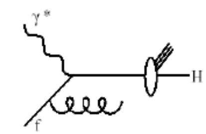
future possibilities/needs for $D(z,\mu)$

- **RHIC/RHIC-II** more luminosity (high p_T hadrons) will yield better bounds

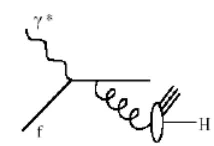
- **e^+e^- (BELLE)** analyze precision measurements of identified hadrons

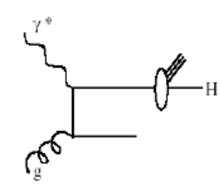
  $\rightarrow$ **gluon fragmentation D_g from scaling violations in e^+e^-**

- **eRHIC** possible precision studies of (polarized) semi-inclusive DIS



$$\frac{d\sigma^h}{dx\,dQ^2\,dz^h} \approx \sum_{f=q,\bar{q}} e_f^2\, f(x,\mu_f)\, D_f^h(z^h,\mu'_f) + \mathcal{O}(\alpha_s)$$

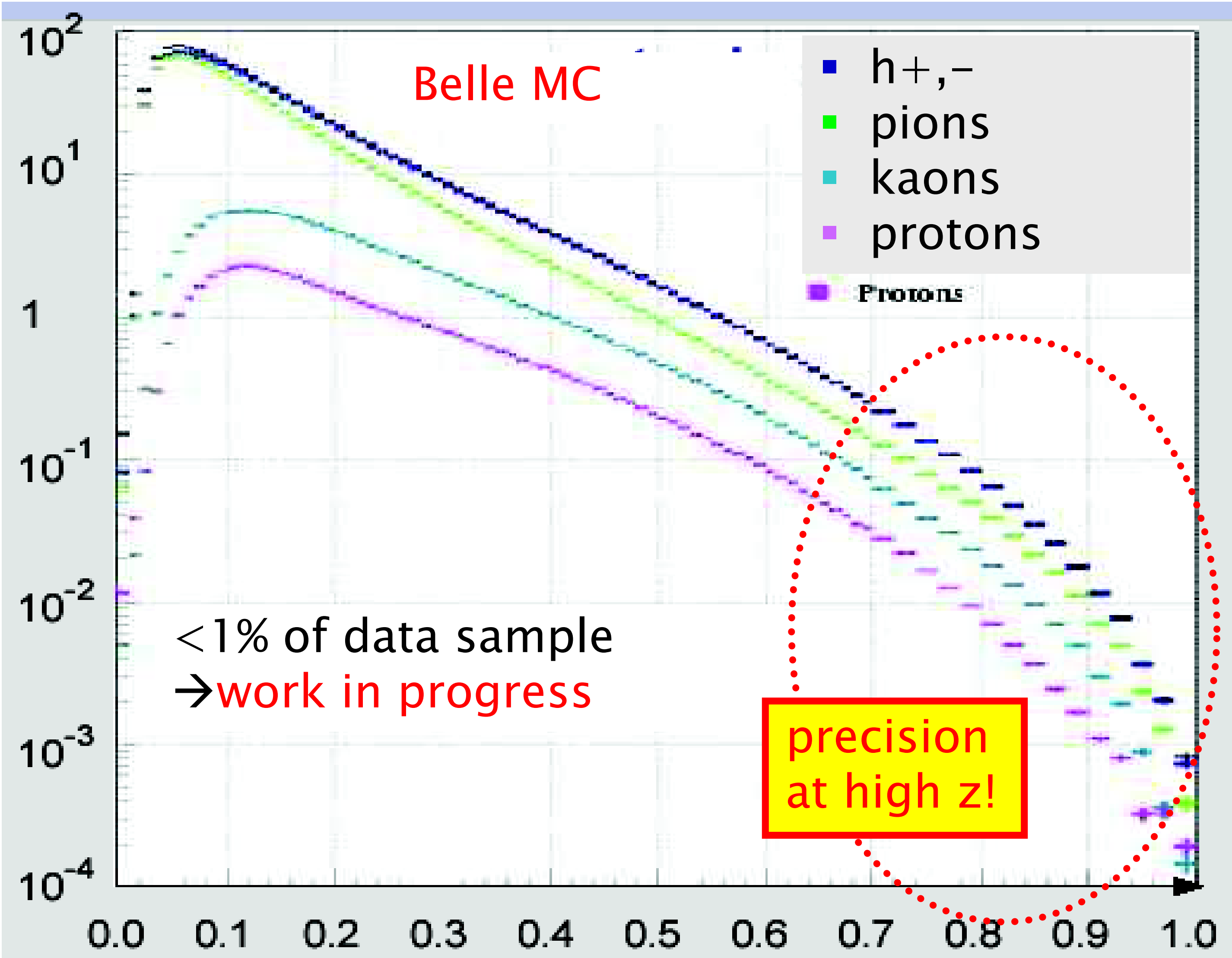




charge separated data for π^+, π^-, K^+, K^-,...

$\rightarrow$ **flavor separation at higher (safer) Q^2**

what can be expected from BELLE



z

R. Seidl, M. Grosse Perdekamp, …

summary & conclusions

found at homepage of R.D. Ball (Edinburgh)